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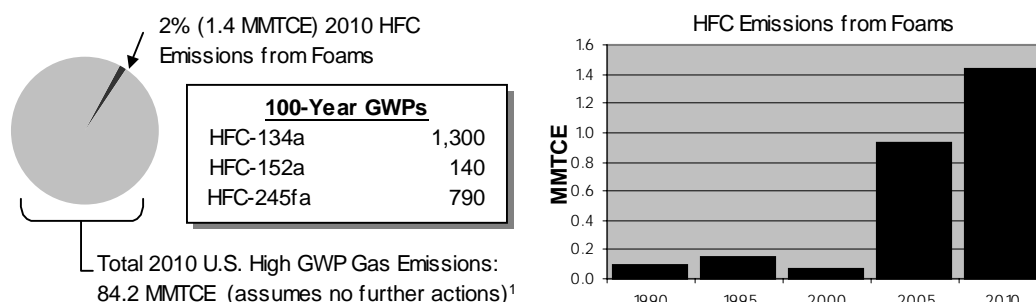
9. Cost and Emission Reduction Analysis of HFC Emissions from Foams in the United States

9.1 Introduction

Various hydrofluorocarbons (HFCs) are used as blowing agents during the manufacture of foams for many end uses. Two such HFCs that are currently available include HFC-134a and HFC-152a. Developmental quantities of HFC-245fa are available, with full-scale production scheduled for 2002. HFC-365mfc might also be used if and when commercialized. These blowing agents might be emitted to the atmosphere during the foam manufacturing process or on-site foam application, while foams are in use, and when foams are discarded. HFC-134a, HFC-152a, and HFC-245fa have 100-year GWPs of 1,300, 140, and 790 times the warming potential of carbon dioxide, respectively. By 2010, under a business-as-usual scenario, the United States could emit 1.4 MMTCE of these HFCs from foams and foam manufacture (See Exhibit 9.1).¹

Historically, chlorofluorocarbons (CFCs) were the primary blowing agents used in the foams industry before they were found to be ozone-depleting substances (ODS). Under the Montreal Protocol, the United States and 22 other nations agreed to phaseout CFCs and to use hydrochlorofluorocarbons (HCFCs) as interim substitutes. Section 610 of the Clean Air Act banned the sale and distribution of most foam products manufactured with HCFCs. “Essential uses” are exempt from this restriction on HCFC use as substitutes and include foam insulation products and foams used for motor vehicle safety that do not have adequate substitutes (EPA, 1993). The most commonly used blowing agents in these

Exhibit 9.1: U.S. Historical and Baseline HFC Emissions from Foams²



¹ An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

² While CFCs and HCFCs are also greenhouse gases, IPCC Guidelines do not include reporting instructions for emissions of ozone depleting substances because they are being phased out under the Montreal Protocol. For purposes of this report, emissions of CFCs and other ODSs from the foam and other sectors are considered to be zero.

sectors were HCFC-141b, HCFC-142b, and HCFC-22. Upon implementation of the HCFC phaseout, which will eliminate import and production of HCFC-141b by 2003 and HCFC-22 and HCFC-142b by 2010, HFCs are expected to capture a larger share of the foam-blowing market. Other potential alternative blowing agents that are applicable in many end uses include hydrocarbons (HCs), water-blown or *in situ* CO₂ (CO₂/water), liquid CO₂ (LCD), and blends of the above.

There are two main types of foams: open cell and closed cell. Open cell foams experience significant blowing agent leakage due to the cell structure. However, because these foams are not typically produced with HFC blowing agents, HFC emissions from this sector are not significant. HFCs are often used in closed cell foam applications for their physical and performance properties. As these foams age, a certain amount of blowing agent may migrate out of the foam. The leakage rate is specific to each foam application, and varies according to the physical properties of the raw materials (e.g., solubility, polymer type, foam cell structure and type of processing) and to the extent that the foam is encapsulated (e.g., type of encasing material, combination of materials, etc.). HFCs can also be emitted at disposal, but a certain amount of blowing agent might remain in closed cell foams permanently.

9.2 Historical and Baseline HFC Emission Estimates

EPA uses a detailed Vintaging Model of ODS-containing equipment and products to estimate the use and emissions of various ODS substitutes, including HFCs and PFCs (See Appendix A). The model tracks the use and emissions of various compounds for the annual “vintages” of new equipment (or products, such as foams) that enter service in each end use. Based largely on data available from industry sources and technical publications, the model estimates ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Fugitive emissions for each end use are estimated by applying annual leak rates and release profiles. The model accounts for ODS substitutes emitted during the manufacturing of foam and for

Exhibit 9.2: U.S. EPA's Vintaging Model Emissions Profile for the Foams Sector

Foams Sector	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total
Flexible PU	NA	NA	NA	NA	NA
Polyisocyanurate Boardstock	10	1.5	50	15	100
Rigid PU Integral Skin	95	2.5	2	0	100
Rigid PU Appliance	4	0.25	15	92.25	100
Rigid PU Commercial Refrigeration	6	0.25	15	90.25	NA
Rigid PU Spray	25	1.5	50	0	100
One Component	100	0	0	0	100
Rigid PU Slabstock and Other	37.5	0.75	15	51.25	100
Phenolic	25	1.125	32	39	100
Polyolefin	95	2.5	2	0	100
XPS Foam Sheet	NA	NA	NA	NA	NA
XPS Boardstock *	NA	NA	NA	NA	NA
Sandwich Panel	10	0.5	50	65	100

Source: EPA estimates.

Notes:

PU – Polyurethane

* This analysis assumes that XPS Boardstock will transition to a non-ODP/non-GWP substitute in 2010.

losses from the foam throughout its lifetime and at disposal (see Exhibit 9.2). By aggregating the data from various end uses, the model produces estimates of annual use and emissions of each compound.

There are several regulatory programs in place, e.g., the Significant New Alternatives Policy (SNAP) Program, to limit use of ODS substitutes in some applications. These programs are expected to result in significant reductions in ODS substitute emissions. These reductions are incorporated in the baseline estimate (see Exhibits 9.3 and 9.4). This cost analysis evaluates the cost of reducing emissions from this baseline.

Exhibit 9.3: Historical U.S. HFC Emissions from the Foam Sector (1990-1999)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)	0.10	0.16	0.22	0.29	0.23	0.15	0.06	0.06	0.06	0.07

Source: EPA estimates.

Notes:

Note that emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the 100-year GWPs listed in the Introduction to the report.

Exhibit 9.4: Baseline U.S. HFC Emissions Forecast for the Foam Sector (2000-2010)

	2000	2005	2010
Emissions (MMTCE)^{a,b}	0.07	0.93	1.43

Source: EPA estimates.

Notes:

Note that emissions are not broken down by chemical to avoid disclosure of confidential business information.

Conversion to MMTCE is based on the GWPs listed in the Introduction to the report.

Forecast emissions are based on a business-as-usual scenario, assuming no further action.

EPA's historical emissions and hypothetical baseline forecast make certain assumptions about market penetration of CFC substitutes:

- HFC-134a was used in certain integral skin foam applications beginning in 1994 (as a result of the non-essential use ban of HCFC substances).
- HFC-152a was used in polyolefin foams beginning in 1994.

Because the HCFC phaseout will eliminate import and production of HCFC-141b by 2003 and HCFC-22 and HCFC-142b by 2010, HFCs are expected to become an important substitute foam-blowing agent in insulating foams, leading to the projected increases in HFC emissions in 2005 and 2010.

9.3 Applicability of Non-HFC Blowing Agents

The foam sector can be divided into three broad categories: thermoset foams, thermoplastic foams, and sandwich panels. Sandwich panels are produced with foams of both types, so this end use is addressed separately. The following section presents a market characterization and technical issues regarding the use of HFCs, and the potential applicability of using hydrocarbons, water-blown CO₂, and liquid CO₂ in the different foam market sectors.

Thermoset Foams

Thermoset foams are produced through a liquid manufacturing process, involving a reaction between a blend of two or three chemicals (e.g. “A”, “B”, and/or “C” sides). Initial conditions are typically room temperature and atmospheric pressure. The reaction increases the temperature of the mix and the viscosity of the reactants. The resultant material is essentially a solid with small gas filled cells throughout (DOW, 2000). Various foam end uses manufactured using this process are discussed below.

Polyurethane (PU) Flexible Foams

Foams from this end use are used in a variety of products, including furniture, bedding, automotive interiors, and carpet underlay. Because of the non-essential use ban under Section 610 of the Clean Air Act, these foams are no longer produced with CFCs or HCFCs. Commonly used ODS alternatives include water-blown CO₂, methylene chloride, acetone, pentane, liquid CO₂, extended-range polyols, additives, accelerated cooling, and variable pressure. HFCs are not expected to be used as blowing agents for this end use (UNEP, 1998). Therefore, this sector is not considered or discussed in this report.

PU Integral Skin Foams

Most integral skin foams are used in the automotive industry for seat cushions, back cushions, armrests, and headrests as well as for general purposes such as shoe soles, skis, and flotation devices. CFC-11 was used as the blowing agent in this application prior to the CFC phaseout. Section 610 of the Clean Air Act banned the sale and distribution of integral skin foam manufactured with HCFCs, so these foams are currently produced using non-ODP blowing agents such as HFC-134a, water-blown CO₂, and hydrocarbons. HFC-134a is primarily used in transportation applications such as armrests and steering wheels as well as shoe soles and flotation devices. HFC-245fa can also be used in this sector (UNEP, 1998; Honeywell, 2000a,b).

Substitute HFC technologies available for flexible integral skin include water-blown CO₂ formulations, which require additional in-mold coatings (IMC) to be injected for some applications, and n-pentane blown foams where very durable skin is required. However, these options might not be as effective in warmer climates due to poorer solubility in polyols. For other sectors such as flexible integral skin shoe soles, water-blown CO₂ is a technically feasible and economically viable option. For rigid integral skin foams, water-blown CO₂ and n-pentane are both technically feasible options (UNEP, 1998).

PU Rigid Foams

PU insulating foams include polyurethane and polyisocyanurate laminate boardstock, appliance, spray, sandwich panels, slabstock, and other foam products. CFC-11, and to a lesser extent CFC-12, were used as the major blowing agents in these applications. HCFC-141b has been the primary replacement for CFCs in polyurethane insulating foams because of similar insulation performance and low capital investment. HCFC-142b, HCFC-22, and blends of the two have also taken a small share of that market. Upon implementation of the HCFC phaseout, these compounds will likely be replaced by non-ODP alternatives such as hydrocarbons, HFCs, and CO₂. Some manufacturers of polyurethane insulating foams (e.g., polyisocyanurate boardstock) have already begun the transition out of HCFCs (UNEP, 1998).

Non-HFC blowing agents applicable to specific end uses in this sector are discussed below.

- **Rigid Polyurethane and Polyisocyanurate Laminated Boardstock.** The primary application for these products is insulation in buildings. Historically, this sector used CFC-11 and then transitioned into HCFC-141b and small amounts of HCFC-141b/22 blends. Viable non-ODP alternatives include hydrocarbons, HFC-245fa, HFC-245fa co-blowing with CO₂/water (HFC-245fa/CO₂), HFC-365mfc, as well as blends of the above (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

Non-HFC options for this sector include hydrocarbons and hydrocarbon blends. Hydrocarbons are being used by at least two U.S. manufacturers (UNEP, 1998; Honeywell, 2000a,b).

- **Rigid PU Appliance and Commercial Refrigeration Foams.** These foams are used in domestic and commercial refrigerators and freezers. CFC-11 was the primary blowing agent used in this sector prior to the CFC phaseout. Currently, the majority of appliance manufacturers use HCFC-141b as a blowing agent, although small amounts of HCFC-142b, HCFC-22, and HFC-134a might be used. HFC-245fa, HFC-134a, and hydrocarbons are all potential non-ODP alternatives. These blowing agents might also be used with small amounts of *in situ* CO₂ (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

The U.S. appliance industry continues to face significant barriers associated with hydrocarbons, such as significant VOC and flammability concerns, as well as energy penalties. *In situ* CO₂ might also be a potential option if: 1) it is used in conjunction with alternative insulation technologies such as vacuum panels (assuming cost and performance issues are solved) and 2) both the external and internal skins are metal, to significantly retard/eliminate diffusion issues (UNEP, 1998; Alliance, 2001).

- **Rigid Spray PU Foam Insulation.** Spray foam (SPF) is primarily used for *in situ* applications of roofing, rigid thermal insulation, and air barriers, usually in residential and commercial buildings, industrial storage tanks, piping and ductwork, and refrigerated transport trailer and tanks. These foams are produced in the field from a hand-held spray gun. Currently, the main blowing agents used in this industry are HCFC-141b and *in situ* CO₂. Potential non-ODP alternatives in this sector include HFC-245fa, HFC-245fa/CO₂, CO₂/water, HFC-365mfc, and hydrocarbons, as well as blends with CO₂ and water (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

In situ CO₂ and hydrocarbons are potential non-HFC blowing agents for this end use. However, key technical issues that need to be addressed for both alternatives include poorer fire performance, dimensional stability, and thermal performance. Despite the significant uncertainties about the details of the transition from HCFC-141b in this sector, EPA believes that for this analysis it is reasonable to assume a range of plausible transition scenarios. EPA plans to work closely with industry to gather additional information as it becomes available to refine this analysis.

In situ CO₂ formulas have a much lower insulation value than HFC formulas, and lower closed cell content. On the processing side, limitations on the minimum ambient processing temperature may act as a considerable constraint in many areas of the United States. While there are some test applications being monitored on roofing applications, it is too early to determine if the foams produced from this technology will perform adequately. In addition, building codes and standards and industry guidelines would have to be changed to allow the use of *in situ* CO₂ blown SPF.

Hydrocarbon blown foams also have challenges that will be more difficult to overcome. The SPF industry is very concerned about the safety of using hydrocarbon blown SPF in field applications. EPA SNAP approval of hydrocarbon blown foam requires the applicator to complete extensive safety training and certification and is limited to only Exxol blowing agents. At this time, an adequate safety program that complies with this requirement has yet to be implemented on a large scale (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

- **Rigid Polyurethane Slabstock.** Slabstock, also known as bunstock, can be fabricated into different shapes and forms, and is used as thermal insulation for a variety of applications including pipes, storage tanks, construction, and refrigerated transport containers. The industry

switched from CFC-11 to HCFC-141b, although there is some use of pentane and water-generated CO₂. Zero-ODP blowing agent alternatives include HFC-245fa, hydrocarbons, *in situ* CO₂ and blends of the above (UNEP, 1998; Honeywell, 2000a,b; Alliance, 2001).

One-Component Foams (OCF)

These foams are used in a variety of building applications such as draft-proofing, sealing door and window frames, and joining insulating panels, roofing boards, and pipe-insulation. Because OCF foams come in pressurized canisters and cylinders, they are also called aerosol foams. OCF blowing agents are typically gaseous, as they function as both a blowing agent and a propellant for the foam. Historically, this sector has primarily used CFC-12, but transitioned into HCFC-142b, HCFC-22, HCFC-142b/22 blends, HFC-134a, HFC-152a, and hydrocarbon blends after the CFC phaseout. Non-ODP options include hydrocarbons, HFC-134a, HFC-152a, HFC-365mfc, and blends of these compounds with HFC-245fa (Honeywell, 2000c,d; UNEP, 1998; Alliance, 2001). Hydrocarbons are currently used for most OCF production (UNEP, 1998; Honeywell, 2000b).

Phenolic Foams

These foams have excellent fire retardant and thermal insulation properties, and have been used in commercial building applications. However, little, if any, phenolic foam is being produced in the United States (EPA, 1993; UNEP, 1998). Consequently, this end use is not considered or discussed in this report.

Thermoplastic Foams

Unlike thermoset foams, thermoplastic foams are not manufactured via chemical reactions. Instead, a plastic resin is melted under high temperature and pressure. As the pressure is released, the blowing agent expands, causing the material to expand. The foaming material is then forced through a small die opening, resulting in a continuous board of desired thickness. When exposed to sufficient heat, thermoplastic foams can melt and return to its polymeric molten state (DOW, 2000). Foams manufactured using this process include polyolefin, expanded polystyrene (EPS), extruded polystyrene (XPS) sheet, and XPS boardstock applications. These end uses and non-HFC blowing agents applicable to this sector are discussed below.

Polyolefin Foams

Polyolefin foams include products made from polyethylene and polypropylene resins. The most common applications for these foams include pipe-wrap insulation, construction materials, protective packaging, flotation devices, and automotive bumper systems. Historically, this sector used CFC-114 and CFC-12, but transitioned into HFC-152a after the CFC phaseout. Most non-insulating applications have now switched to isobutane, but HCFC-142b and HCFC-142b/22 blends are still being used in the production of pipe-wrap insulation. Some manufacturers might also be using HFC-134a and HFC-152a. Non-ODP alternatives include HFC-134a, HFC-152a, hydrocarbons, and LCD (UNEP, 1998; Honeywell, 2000b; Alliance, 2001).

XPS Sheet

These foams are used in a variety of applications including food service and food packaging products such as single-service plates, cups, and egg cartons, and protective packaging for furniture and electronic devices. For these applications, a thermoforming manufacturing process is used. Other applications included laminated sheets, which are typically used in insulating sheathing applications. Historically, foams were primarily produced with CFC-12 as a blowing agent. Following the CFC phaseout, the vast

majority of U.S. XPS sheet thermoforming manufacturers transitioned directly into hydrocarbons. Some amount of HFC-152a is used in regions where VOCs are a concern (UNEP, 1998; Alliance, 2001).

XPS Boardstock

These foams are used for insulation purposes for roofs, floors, walls, tile and plaster backing applications, as well as being core material for sandwich panel construction and a small number of specialty applications. HCFC-142b and a blend of HCFC-22/HCFC-142b are the most common replacements for CFCs in insulating XPS boardstock. In anticipation of the 2010 phaseout date for HCFC-142b and HCFC-22, the XPS industry is researching alternatives to HCFCs. This research includes HFCs and hydrocarbons, blends of these alternatives with water-blown CO₂, and LCD (DOW, 2000; FPSA, 2000; Honeywell, 2000b; UNEP, 1998).

Several European manufacturers have begun to implement non-HCFC alternatives. However, options that are viable in Europe might not be directly applicable to the United States because the markets differ: the Europeans value strength and compressibility, while the U.S. market places a premium on insulating properties and low density (FPSA, 2000). U.S. manufacturers hope to continue to use HCFC-142b and HCFC-22 until the 2010 phaseout date (DOW, 2000). Given the length of time before this phaseout and the related uncertainties in the U.S. transition, no assumptions will be made at this point on what specific alternatives will ultimately be implemented in the United States for XPS boardstock. Thus, this leads to a default assumption that whatever alternatives are implemented will not have any greenhouse gas emissions; the Agency recognizes that more accurate projections will be possible as the 2010 phaseout date approaches.

EPS Foam

EPS boards and sheets are distinguished by its associated manufacturing process, typically steam molding. EPS products historically did not use CFCs as the blowing agent. Thus, any calculations regarding HFC emission contributions or reductions from sheet applications will be limited to XPS sheathing insulation products for the purposes of this chapter (Alliance, 2001).

Sandwich panels

This end use is so named because it consists of foam cores between rigid facings. These foams are valued for their insulating and self-adhesive qualities, and are used in various applications including doors, panels, water heaters, cold storage, and in the transport industry for insulated trucks and reefers. Historically, CFC-11 was the primary blowing agent used in this application. Today, the industry is mainly using HCFC-141b, although HCFC-22, HCFC-142b, HFC-134a, water-blown CO₂, hydrocarbons, and blends of the above are being used by specific end uses. Following the HCFC phaseout, the likely blowing agents include HFC-245fa, HFC-134a, HFC-152a, CO₂/water, LCD, and blends of the above (UNEP, 1998; Honeywell, 2000a,b).

Water-blown CO₂, hydrocarbons, and LCD are all potential non-HFC alternatives in this sector (UNEP, 1998; Honeywell, 2000a,b). Because this end use is comprised of thermoset and thermoplastic foams, the choice of blowing agent substitute depends on the specific application. In polyurethane and XPS foam insulating applications, the use of non-HFC blowing agents might result in poorer thermal performance, necessitating an increase in foam thickness to achieve comparable R-values. Thus, using non-HFC substitutes might create space constraints in areas such as refrigerated transport and walk-in-coolers for cold storage. Other key technical issues that need to be addressed in order to remain effective in sandwich panel applications include fire performance and dimensional stability (Alliance, 2001).

The applicability of hydrocarbons, LCD, and *in situ* CO₂ to various foam end uses are summarized in Exhibit 9.5.

Exhibit 9.5: Potential Applicability of Non-HFC Blowing Agents to Various End uses in the Foams Sector

End use	HFCs	LCD	<i>In situ</i> CO ₂	Source
Flexible Polyurethane	✓	✓	✓	UNEP (1998)
Polyisocyanurate Boardstock	✓			UNEP (1998)
Rigid PU Integral Skin	✓	✓		UNEP (1998)
Rigid PU Appliance	✓		✓	UNEP (1998), Alliance (2001)
Rigid PU Commercial Refrigeration	✓		✓	UNEP (1998)
Rigid PU Spray	✓		✓	UNEP (1998), Industry Communications
One Component	✓			UNEP (1998)
Rigid PU Slabstock	✓			UNEP (1998)
Phenolic	✓			UNEP (1998)
Polyolefin	✓	✓		UNEP (1998)
XPS Foam Sheet	✓	✓		UNEP (1998)
XPS Boardstock	✓	✓		UNEP (1998), Honeywell (2001a)
Sandwich Panel	✓	✓	✓	UNEP (1998), Honeywell (2001a)

Notes:

Only end uses which are currently using HFCs are listed.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

9.4 Cost Analysis

This section presents a cost analysis of achieving HFC emissions reductions from the 2010 baseline presented in Exhibit 9.4. A discounted cash-flow analysis was conducted to estimate break-even carbon prices in dollars per metric ton of carbon equivalent (TCE) associated with each blowing agent substitution. The model determined the net present value for each non-HFC alternative from an annual stream of cash flows, based on a start-up capital cost, annual variable costs, annual indirect costs, and annual revenue obtained from sales of emission reduction credits.³ The price of carbon was the unknown factor in determining revenue. The model solved for the value of carbon that would make the net present value of this cash flow equal to zero (i.e., the break-even carbon price). The analysis assumed a project lifetime of 25 years and was performed at discount rates of four and eight percent.

Emissions were addressed using a Life Cycle Climate Performance (LCCP) approach, which accounts for the following:

- HFC emission reductions from blowing-agent substitution,
- indirect emissions of CO₂ associated with energy efficiency differences resulting from the substitution (unless otherwise stated), and
- embodied energy and fugitive emissions from the manufacture of the HFC.⁴

Costs were based on the incremental differences between using the HFC and switching to the non-HFC. Financial information considered in the analysis include:

³ Emission reduction credits were HFC emission reductions achieved by the blowing agent substitution offset by indirect emissions due to energy efficiency discrepancies.

⁴ Embodied energy and fugitive emissions from the manufacture of the HFC are accounted for by adjusting the 100-year GWP used in the analysis, per the methodology described in Appendix A of Dieckmann and Magid (1999).

- capital costs, which account for equipment costs to modify existing plants and to maintain production capacity,
- blowing agent costs, which address the difference between costs and the quantity of the HFC and non-HFC alternative required,
- foam costs, which address changes in foam density, the amount of fire retardant used, the quantity and type of polyol, etc.,
- testing, training or other costs associated with transitioning to non-HFC alternatives, and
- indirect costs from energy efficiency differences (unless otherwise stated).

Conversion or “learning curve” costs, which consider short-term costs incurred due to yield, rate, and density penalties associated with conversion uncertainties as well as technical support costs, could not be addressed in the analysis because this type of information was not readily-available.

Reliable financial information is available for only two end uses: 1) PU spray foams and 2) PU appliance foams. Thus, only the results of the cost analysis for these applications and a summary are presented below.

PU Spray Foams

This analysis was based on a hypothetical spray foam contractor who produces approximately 127,000 pounds of foam using a 50/50 blend of HFC-245fa and CO₂ (water) as a blowing agent. The blowing agent constitutes approximately 10 percent of the foam, by weight. Various “base case” inputs and assumptions are presented in Exhibit 9.6. This cost analysis estimates the break-even carbon price for this hypothetical contractor to replace HFC-245fa/CO₂ (water) with two non-HFC blowing agents: 1) CO₂ (water) and 2) hydrocarbons. The foams manufactured with the two alternatives are assumed to compensate for lower insulating performance relative to HFC-blown foams by increasing the thickness and density of the foam. Thus, incremental differences in indirect emissions and costs associated with energy penalties are negligible.

Exhibit 9.6: Base Case Assumptions for a Hypothetical Spray Foam Contractor Using HFC-245fa/CO₂ (water)

Variable	Unit	Value	Source
Foam Produced	Lbs	127,000	Calculated
Blowing Agent Component of Foam	%	10	Industry Communication
Blowing Agent Consumption	Lbs	12,700	Estimated from Caleb (2001)
Foam Cost	\$/lbs	Approximately \$1 *	Assumption
Price of Isocyanate	\$/lb	1.00	Industry Communication
Price of HFC-245fa	\$/lb	4.00	Caleb (2001)

Notes:

* Approximate value based on available foam costs for appliances and water heaters.

“Industry Communications” are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

Cost factors that are addressed include:

- fire testing costs incurred by system houses for various formulations;
- capital equipment costs;
- employee training costs (hydrocarbons only);
- increased cost of foam components (e.g., polyols, additives, etc.);

- increased consumption of foam components to compensate for increased foam density;
- increased use of fire retardant; and
- incremental differences in the costs of blowing agents and the quantity required.

Annual emission reductions were determined based on the estimated amount of blowing-agent consumed by the hypothetical contractor and from the blowing-agent release profile used in the Vintaging Model (Exhibit 9.2).

Assumptions, the break-even carbon price, and the potential emission reductions in 2010 specific to each blowing agent substitution are presented below.

Replacing HFC-245fa/CO₂ (water) with CO₂ (water)

Assumptions specific to this substitution are presented in Exhibit 9.7. To be cost-effective, replacing HFC-134a with cyclopentane would require a carbon price of approximately \$114/TCE and \$123/TCE, at discount rates of four and eight percent, respectively. This substitution can potentially reduce about 0.5 MMTCE in 2010, or approximately 35 percent of baseline emissions from the foams sector.

Replacing HFC-245fa/CO₂ (water) with Hydrocarbons

Assumptions specific to this substitution are presented in Exhibit 9.8. An additional cost factored into the analysis for this alternative was the additional cost of training workers in handling, storing, and using hydrocarbons. Based on the assumptions made, it is estimated that replacing HFC-245fa/CO₂(water) with hydrocarbons would require a carbon price of approximately \$-16/TCE at both discount rates of four and eight percent. This substitution can potentially reduce about 0.5 MMTCE in 2010, or approximately 35 percent of baseline emissions from the foams sector. The Agency recognizes that this option may not be implemented because of safety and liability concerns.

Exhibit 9.7: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂ (water) with CO₂ (water)

Variable	Unit	Value	Source
Capital Costs	\$	Negligible ^a	Industry Communication
Fire Testing Costs	\$/Contractor	4,000 ^b	Caleb (2001), Industry Communication
Increased Fire Retardant Use	%	1	Assumption
Cost of Fire Retardant	\$/lb	2.00	Industry Communication
Price of Isocyanate	\$/lb	1.00	Industry Communication
Blowing Agent Component of Foam	%	6	Industry Communication
Increase in Foam Density	%	30 ^c	Industry Communication
Assumed Increase in Cost of Foam	\$/lbs	0.10	Assumption

Notes:

^a Assumes that contractors that are using HFC-245fa/CO₂ (water) have equipment that can use CO₂ (water) with minimal modification.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001; Industry Communication).

^c Assumes that foam density increases from 2.5 lb/ft³ to 3.25 lb/ft³.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

Exhibit 9.8: Assumptions and costs used in the cost analysis to substitute HFC-245fa/CO₂(water) with Hydrocarbons

Variable	Unit	Value	Source
Capital Costs	\$	10,000 ^a	Industry Communication
Fire Testing Costs	\$/Contractor	4,000 ^b	Caleb (2001), Industry Communication
Increased Fire Retardant Use	%	3	Assumption
Cost of Fire Retardant	\$/lb	2.00	Industry Communication
Price of Cyclopentane	\$/lb	0.90	Industry Communication
Blowing Agent Component of Foam	%	9	Industry Communication
Increase in Foam Density	%	20 ^c	Industry Communication
Assumed Increase in Cost of Foam	\$/lbs	0.10	Assumption
Employee Training Costs	\$/yr	\$6400 ^d	Industry Communication

Notes:

^a Assumes that technical issues can be resolved.

^b Based on \$250,000 per systems house, 20 systems houses, and approximately 1,250 spray foam contractors (Caleb, 2001; Industry Communication).

^c Assumes that foam density increases from 2.5 lb/ft³ to 3.0 lb/ft³.

^d Assumes a cost of approximately \$215/employee/day, 2 crews of 3 employees (total of 6 employees), and 5 days of training.

"Industry Communications" are based on communications with multiple chemical producers, equipment manufacturers, and trade associations.

PU Appliance Foams

Two blowing agent substitution options were considered for this end use:

- replacing HFC-134a with cyclopentane; and
- replacing HFC-245fa with cyclopentane.

This cost analysis was based on a hypothetical facility that manufactured approximately 540,000 refrigerators and consumed about 3.4 million pounds of blowing agent annually. The blowing agent was assumed to constitute approximately 12 percent of the foam. The costs of producing a refrigerator using each blowing-agent (e.g., HFC-134a, HFC-245fa, and cyclopentane) were provided by the refrigeration industry. Factors considered in these data include:

- capital costs to convert;
- blowing agent costs;
- foam costs (including density considerations);
- liner costs; and
- additional costs required to meet the 2001 National Appliance Energy Conservation Act (NAECA) energy efficiency standards.

Data have been aggregated to protect confidential information.

HFC emission reductions over time were derived from the blowing agent release profile used in the Vintaging Model (Exhibit 9.2), which accounts for release during manufacturing, annual leakage, and at disposal. Because the cost data assumes that the refrigerators manufactured using various blowing agents meet the same energy efficiency standards, incremental differences in indirect emissions and costs between the blowing agents are assumed to be negligible.

Replacing HFC-134a with Cyclopentane

To be cost-effective, replacing HFC-134a with cyclopentane would require a carbon price of approximately \$17/TCE and \$43/TCE, at discount rates of four and eight percent, respectively. This

substitution can potentially reduce about 0.03 MMTCE in 2010, or approximately two percent of baseline emissions from the foams sector.

Replacing HFC-245fa with Cyclopentane

To be cost-effective, replacing HFC-245fa with cyclopentane would require a carbon price of approximately \$229/TCE and \$341/TCE, at discount rates of four and eight percent, respectively. This substitution can potentially reduce about 0.19 MMTCE in 2010, or approximately 13 percent of baseline emissions from the foams sector. Because this analysis only addresses substitutions with break-even costs below \$200/TCE, this alternative is not listed in Exhibit 9.9.

Summary

Overall, assuming these hypothetical transitions to non-HFC alternatives are implemented, HFC reductions would total 1.03 MMTCE, or 72 percent of 2010 baseline estimates from the foams sector. Exhibit 9.9 summarizes HFC emission reductions by cost per metric ton of carbon equivalent for the year 2010 at discount rates of four and eight percent.

Exhibit 9.9 Emission Reductions and Costs in 2010						
Option	Break-even Cost (\$/TCE)		Incremental Reductions		Sum of Reductions	
	Discount Rate					
	4%	8%	MMTCE	Percent	MMTCE	Percent
PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with hydrocarbons	(15.70)	(15.64)	0.5	35%	0.5	35%
PU Appliance Foams - Replace HFC-134a with cyclopentane	17.18	43.25	0.03	2%	0.53	37%
PU Spray Foams - Replace HFC-245fa/ CO ₂ (water) with CO ₂ (water)	114.09	123.52	0.5	35%	1.03	72%
Notes:						
2010 baseline emissions from the foam blowing sector equal 1.43 MMTCE.						
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.						
Sums might not add to total due to rounding.						

9.5 References

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Appendix 9.1: Description of HFC Emission Reduction Technologies and Practices

Opportunities to reduce HFC emissions from foams fall into the following categories: non-HFC blowing agents, use of lower GWP HFCs, alternative insulation technologies, and direct emission reduction. These options are discussed below.

Non-HFC Blowing Agents

The following section summarizes potential non-HFC blowing agents for various foam end uses. Three options are discussed below: hydrocarbons, water-blown CO₂, and liquid CO₂.

Hydrocarbons (HC)

Hydrocarbons such as propane, butane, isobutane, n-pentane, isopentane, cyclopentane, and isomers of hexane are SNAP-approved alternatives to HFCs. HCs are inexpensive and have lower GWP impacts relative to HFCs. However, key technical issues associated with hydrocarbons are:

- **Flammability.** HCs require stringent safety precautions in manufacturing, storage, handling, transport, and customer use, which necessitate factory upgrades and employee training. Specialized equipment that might be needed includes a dedicated storage tank for the hydrocarbon, pre-mixers, adapted high-pressure dispensers, suitable molds plus process exhaust, hydrocarbon detectors, and appropriate classification of electrical equipment. In order to reduce fire risks, some applications might also require the use of a larger quantity of flame-retardants and/or the use of a more expensive fire-retardant.
- **Volatile Organic Compounds (VOCs).** Because HCs contribute to ground level ozone and smog, they are highly regulated by the government. In many parts of the United States, HCs cannot be used without emission controls, which can significantly increase the costs of conversion.
- **Performance.** Some HCs only yield approximately 85 percent of the insulating value of HCFC-141b and HFC-245fa. Producing a thicker foam can compensate for this energy efficiency difference, but will increase the cost of production. This option might not be viable in fixed thickness applications such as appliances, or in applications where R-value is proscribed by code such as in PU spray roofing insulation. Other performance considerations include dimensional stability and solubility. Addressing these factors might require a more expensive and more limited polyol formulation.

Costs of converting to hydrocarbons and addressing technical considerations can be significant, but vary according to factory-specific needs. In spite of these issues, hydrocarbons are being considered in a wide variety of applications (UNEP, 1998; Alliance, 2000; Alliance, 2001;).

Liquid Carbon Dioxide (LCD)

The basic principle by which LCD blowing agents operate is expansion of liquid CO₂ to the gaseous state. Liquid CO₂ is blended with other foam components under pressure prior to the initiation of the chemical reaction. When decompressed, the CO₂ expands, resulting in the froth foam, which further expands with the additional release from the water/isocyanate reaction. LCD might require formulation changes to more readily dissolve the CO₂ and to prevent deactivation of PU catalysts. When LCD is introduced at the head, often referred to as third stream, the metering equipment can be quite complicated and, to date, unreliable. Difficulties encountered in using LCD include the limited solubility of the

chemical mixture, controlled decompression, and distribution of the unavoidable froth (UNEP, 1998). Foams blown with CO₂ might suffer from lower thermal conductivity, lower dimensional stability, and higher density versus HCFC blown foams. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams *et al.*, 1999; Honeywell, 2000a; Alliance, 2001).

Water-Blown (*in situ*) Carbon Dioxide (CO₂/water)

In this process, CO₂ produced from a chemical reaction between water and polymeric isocyanate is used as a blowing agent. During manufacturing, no ODP or high GWP gases are emitted, and there are limited health and safety risks during processing. However, foams produced using CO₂/water are subject to the same performance limitations discussed for LCD-blown foams: lower thermal conductivity, lower dimensional stability, and higher density versus HCFC- and HFC- blown foams. LCD and CO₂ are generated *in situ*. In some PU foam applications, a major concern associated with using water-generated or LCD systems is the increased percentage of open cell content, which results in poorer water-proofing performance in water-proofing quality of the final product. Another consideration is that the polymeric isocyanurate content must be increased, which cannot be accommodated by some spray foam equipment. To overcome these limitations, CO₂ can be blended with hydrocarbons or HFCs (Williams *et al.*, 1999; Honeywell, 2000a; Alliance, 2001).

Although LCD and CO₂ generated *in situ* have similar performance issues, the process limitations associated with each differ. Less mechanical modifications are required to use *in situ* CO₂, and the foam manufacturer or spray foam applicator can be more certain of the final CO₂ content, and overall foam properties, than for LCD (Alliance, 2001).

Lower-GWP HFC Substitution

Manufacturers can reduce their emissions on a carbon basis by switching from a blowing agent with a high GWP to one with a lower GWP, but any associated energy penalties must also be considered. Because choices of blowing agents are driven by performance and economic considerations (factors such as utility, functionality, solubility, vapor pressure tolerance, and cost) rather than GWP, options will vary depending on the type of foam (i.e., thermoset or thermoplastic), the manufacturing process, and the specific end use application.

Currently, HFC-134a is the most common HFC used in the foam industry and has a GWP of 1,300. HFC-245fa has a GWP of 790, and is expected to be commercially available in the United States by mid-2002. It has been identified as an effective substitute for many applications, including rigid and integral skin polyurethane. Initial industry reports indicate that HFC-245fa-blown foams have properties much improved over HFC-134a foams, and, for many applications, are comparable to those using CFCs or HCFCs (Honeywell, 2000a). Companies can potentially produce higher quality foams and reduce emissions on a carbon equivalent basis by substituting HFC-134a with HFC-245fa.

Due to lack of cost information, this HFC reduction option is not discussed further.

Alternative Insulation Materials and Technologies

Alternative insulation technologies in certain construction applications include fiberboard, fiber glass, and cellular glass. However, users often still select fluorocarbon foams because of superior properties such as fire resistance, structural rigidity, moisture resistance, and insulation effectiveness, even though they may be more expensive (March Consulting Group, 1998).

Vacuum panels have insulating capabilities significantly better than any foam insulation available today, and offer tremendous potential for the refrigeration industry. They are typically open-celled polyurethane or polystyrene foam encapsulated in a gas barrier. This assembly is then evacuated to give the panel its insulating properties. Implementation of this technology has been limited due to its high

costs. Any future use of vacuum panels in the United States will depend on overcoming technical hurdles, significantly lowering the cost and gaining application and building code acceptance. Currently, vacuum panels are only SNAP approved for the rigid polyurethane appliance sector (Tao *et al.*, 1996; Dieckmann and Magid, 1999; Honeywell, 2000b).

More research is needed to determine the potential of these alternative technologies to displace foams blown using high-GWP gases. Because reliable cost information is not available, these HFC emission reductions are not discussed further.

Direct Emission Reduction

Direct emission reduction opportunities vary according to the type of foam in question and the application to which it is put. Various measures could be adopted in each of the phases of production, usage, and decommissioning. Examples include capture of the vapor at the “head” and use of lower permeability facings. Proper recovery and recycling or destruction by means of incineration are also potential means of abating HFC emissions. It is difficult to generalize the potential emission savings or costs associated with these abatement options (March Consulting Group, 1998). However, recovery at de-commissioning currently is not considered economically or technologically feasible. Consequently, this reduction option is not discussed further.